

The local supermassive black hole mass density: corrections for dependencies on the Hubble constant

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ABSTRACT

We have investigated past measurements of the local supermassive black hole mass density, correcting for hitherto unknown dependencies on the Hubble constant, which, in some cases, had led to an underestimation of the mass density by factors of ~ 2 . Correcting for this, we note that the majority of (but not all) past studies yield a local supermassive black hole mass density that is consistent with the range $4.4\text{--}5.9 \times 10^5 f(H_0) M_\odot \text{ Mpc}^{-3}$ (when using $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$). In addition, we address a number of ways in which these past estimates can be further developed. In particular, we tabulate realistic bulge-to-total flux ratios which can be used to estimate the luminosity of bulges and subsequently their central black hole masses.

Key words: black hole physics — galaxies: bulges — cosmology: cosmological parameters

1 INTRODUCTION

Assuming that the dark mass concentrations at the centres of both elliptical galaxies and the bulges of disc galaxies are the sleeping engines that powered past quasar activity (e.g. Miller 2006; Brand et al. 2005, and references therein), then the local mass density of such quiescent supermassive black holes (SMBHs), $\rho_{\text{bh},0}$, can be used to constrain models of quasar formation and growth (e.g. Haehnelt & Kauffmann 2001; Bromley, Sommerville & Fabian 2004; Yu & Lu 2004; Hopkins, Richards & Hernquist 2006). After factoring in potential SMBH mass-energy losses due to gravitational radiation (Ciotti & van Albada 2001; Yu & Tremaine 2002; Menou & Haiman 2004) and the possibility of lost mass from either “three-body” SMBH slingshot ejection (e.g. Volonteri, Haardt & Madau 2003; Hoffman & Loeb 2007) or expulsion via gravitational radiation recoil (e.g. Merritt et al. 2004; Libeskind et al. 2006) $\rho_{\text{bh},0}$ helps constrain the amount of material to explain past quasar flux.

Together with the quasar luminosity function (e.g. Hopkins et al. 2005, and references therein) integrated over time, $\rho_{\text{bh},0}$ can also constrain the average efficiency at which matter is converted to radiation as it falls onto a SMBH (e.g. Ciotti, Haiman & Ostriker 2001; Elvis et al. 2002; Ferrarese 2002; Yu & Tremaine 2002; Fabian 2003; Marconi et al. 2004; Merloni 2004; Shankar et al. 2004; Yu & Lu 2004). This can

in turn tell us about the rotation of SMBHs. For example, a non-rotating Schwarzschild black hole is expected to have an efficiency of 5.4 per cent while a maximally rotating Kerr black hole may have an efficiency as great as 37 per cent (Thorne 1974; Hasinger 2005). Radiative efficiencies are typically reported to range around 10–15 per cent but values as high as $\sim 30\text{--}37$ per cent are also sometimes reported (e.g. Gallo et al. 2004; Crummy et al. 2006; Wang et al. 2006).

For the above reasons it is of interest to accurately determine $\rho_{\text{bh},0}$. In an attempt to help explain some of the differences between previously reported values (Table 1), we will discuss a number of corrections and adjustments that could be made to past estimates. We focus on how estimates of $\rho_{\text{bh},0}$ depend on the Hubble constant, and how past measurements which have not fully taken this into account are affected — sometimes changing by factors of 2 or more. We shall refer to these revised estimates of $\rho_{\text{bh},0}$ (Section 2) as our “ h -corrected values”. In addition we raise a number of other points pertaining to the accurate estimation of the local SMBH mass density, mostly addressing the issue of recovering the host bulge luminosity before converting this into a SMBH mass. Section 3 provides a summary.

2 ILLUSTRATIVE STUDIES

The nature of the hidden or over-looked dependencies on the Hubble constant are endemic to most past estimates of

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Table 1. Local SMBH mass density estimates. The factor $h_{70}^3 = [H_0/(70 \text{ km s}^{-1} \text{ Mpc}^{-1})]^3$ is appropriate for the Graham et al. (2007) study because the $M_{\text{bh}}-n$ relation they used is independent of the Hubble constant. The majority of the densities from other papers have been transformed to $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ using h^2 rather than h^3 , as indicated in each paper. However, as shown in Table 3, this is not always appropriate.

Study	$\rho_{\text{bh},0} (\text{E/S0})$ $h_{70}^2 10^5 M_{\odot} \text{ Mpc}^{-3}$	$\rho_{\text{bh},0} (\text{Sp})$ $h_{70}^2 10^5 M_{\odot} \text{ Mpc}^{-3}$	$\rho_{\text{bh},0} (\text{total})$ $h_{70}^2 10^5 M_{\odot} \text{ Mpc}^{-3}$
Graham et al. (2007)	$(3.46 \pm 1.16)h_{70}$	$(0.95 \pm 0.49)h_{70}$	$(4.41 \pm 1.67)h_{70}$
Wyithe (2006)	...	...	2.28 ± 0.44
Fukugita & Peebles (2004) ^a	$(3.4^{+3.4}_{-1.7})h_{70}^{-1}$	$(1.7^{+1.7}_{-0.8})h_{70}^{-1}$	$(5.1^{+3.8}_{-1.9})h_{70}^{-1}$
Marconi et al. (2004)	3.3	1.3	$4.6^{+1.9}_{-1.4}$
Shankar et al. (2004) ^b	$3.1^{+0.9}_{-0.8}$	$1.1^{+0.5}_{-0.5}$	$4.2^{+1.1}_{-1.1}$
Shankar et al. (2004) ^c	$3.0^{+1.0}_{-0.6}$	$1.2^{+0.4}_{-0.2}$	$4.2^{+1.1}_{-0.6}$
McLure & Dunlop (2004)	2.8 ± 0.4	...	...
Wyithe & Loeb (2003)	...	...	$2.2^{+3.9}_{-1.4}$
Aller & Richstone (2002) ^d	1.8 ± 0.6	0.6 ± 0.5	2.4 ± 0.8
Yu & Tremaine (2002) ^e	2.0 ± 0.2	0.9 ± 0.2	2.9 ± 0.4
Merritt & Ferrarese (2001) ^f	...	...	$4.6h_{70}^{-1}$
Salucci et al. (1999)	6.2	2.0	8.2

^a See their equation 75.

^b Based on their Section 3.2.

^c Based on their Section 3.4.

^d Taken from their Table 2.

^e Based on their $(M_{\text{bh}}-\sigma)$ -derived mass function.

^f See also Ferrarese (2002).

$\rho_{\text{bh},0}$. It is therefore necessary to only look at a couple of representative case studies in detail, and provide the revised estimates from other studies in tabular form (Table 3). In what follows, we have chosen two interesting and well written studies.

2.1 Case study 1

Our first example is the analysis by Aller & Richstone (2002, hereafter AR02), who used the $L-\sigma$ relation (e.g. Faber & Jackson 1976) to convert luminosities into velocity dispersions and then applied the $M_{\text{bh}}-\sigma$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000) to obtain a histogram of SMBH masses. We have identified two areas for improvement pertaining to the treatment of the Hubble constant.

The first is in regard to their adjustment of the Tremaine et al. (2002) $M_{\text{bh}}-\sigma$ relation for what they referred to as a correction from $h = 0.8$ to $h = 1$, where $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Had all, or at least the majority of, the SMBH masses used to construct the Tremaine et al. relation been obtained with distances that depended on an assumed Hubble constant of $80 \text{ km s}^{-1} \text{ Mpc}^{-1}$, then it would be appropriate to multiply (decrease) the SMBH masses by a factor of 0.8 to make the $M_{\text{bh}}-\sigma$ relation consistent with a Hubble constant of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (AR02, their equation 23). However, only five of the 31 galaxies used to construct the Tremaine et al. relation had distances, and thus SMBH masses, derived using a Hubble constant of $80 \text{ km s}^{-1} \text{ Mpc}^{-1}$; most galaxies had their distances obtained using surface brightness fluctuations (Tonry et al. 2001). Removal of the five galaxies with distances obtained using $H_0 = 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$ changes neither the slope nor intercept of the Tremaine et al. $M_{\text{bh}}-\sigma$ relation by more than 0.01. This relation is therefore effectively independent of the Hubble

constant and need not be adjusted. Consequently, the total SMBH mass density in AR02 should be 25 per cent higher and scale with h^3 rather than h^2 . Similarly, the h -correction in Yu & Tremaine (2002, after their equation 6) which was applied to Tremaine et al.'s (2002) $M_{\text{bh}}-\sigma$ relation should also not have been applied.

The SMBH masses that were computed by AR02 are dependent on their adopted Hubble constant for a second reason: their SMBH mass estimates were derived from absolute magnitudes which depend on h . This SMBH dependence on h can be seen in the χ term which appears in their equation 25, and which is defined in their equation 22. Removing the aforementioned factor $0.8/h$ from their equation 25, one has $M_{\text{bh}} \propto h^{-4.02 \times 5/7.7} \propto h^{-2.61}$. That is, their M_* term varies with $h^{-2.61}$. This has apparently gone over-looked in the literature to date.

Now, AR02's equation 24 for the SMBH mass function, which is in units of M_{bh} (rather than $\log M_{\text{bh}}$) and which depends on M_* , can be written as

$$\frac{dN}{dM_{\text{bh}}} = \frac{h^3 \phi_*}{M_* h^{-2.61}} \left(\frac{M_{\text{bh}}}{M_* h^{-2.61}} \right)^\alpha \exp \left[- \left(\frac{M_{\text{bh}}}{M_* h^{-2.61}} \right)^\beta \right]. \quad (1)$$

The expression for the SMBH mass density is thus

$$\begin{aligned} \rho_{\text{bh}} &= \int_{M_{\text{min}}}^{M_{\text{max}}} M_{\text{bh}} \frac{dN}{dM_{\text{bh}}} dM_{\text{bh}} \\ &= h^3 \phi_* \frac{M_* h^{-2.61}}{\beta} \left\{ \gamma \left[\frac{\alpha + 2}{\beta}, \left(\frac{M_{\text{max}}}{M_* h^{-2.61}} \right)^\beta \right] \right. \\ &\quad \left. - \gamma \left[\frac{\alpha + 2}{\beta}, \left(\frac{M_{\text{min}}}{M_* h^{-2.61}} \right)^\beta \right] \right\}, \end{aligned} \quad (2)$$

where $\gamma(a, x)$ is the incomplete gamma function (e.g. Press et al. 1992) defined by

$$\gamma(a, x) = \int_0^x e^{-t} t^{a-1} dt. \quad (3)$$

The SMBH mass density in AR02 therefore actually varies with $h^{3-2.61} = h^{0.39}$ (not h^2 as given in AR02) and it also varies with an additional complicated dependence on h which is tied up in the gamma functions above. Correcting AR02's SMBH mass density to $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and integrating down to a minimum mass of $10^6 M_\odot$, as they did, one obtains a value of $\rho_{\text{bh}} = 5.9 \times 10^5 M_\odot \text{ Mpc}^{-3}$. This value is ~ 2.5 times larger than what AR02 find when $h = 0.7$ (see their equation 28).

This type of correction is again not unique to the analysis in AR02, for example, McLure & Dunlop's (2004) estimate of ρ_{bh} for E/S0s, increases from $2.8 \times 10^5 M_\odot \text{ Mpc}^{-3}$ to $4.8 \times 10^5 M_\odot \text{ Mpc}^{-3}$ (for $h = 0.7$, see Graham et al. 2007, their Section 4). In general, all SMBH mass functions which have been derived from h -dependent galaxy luminosities will depend on h in a similar fashion, although the above factor of 2.61 may vary from paper to paper (see Table 3).

2.1.1 Related issues

Ignoring the above mentioned dependencies on the Hubble constant for the moment, it is expected that the SMBH masses in AR02 are too high at the low-mass end because of a) the way they converted disc galaxy magnitudes into bulge magnitudes, and b) the way they assigned a velocity dispersion to these magnitudes. The average bulge-to-disc (B/D) luminosity ratios which AR02 assigned to their early- and late-type spiral galaxies, and also lenticular galaxies, came from the $R^{1/4}$ -bulge plus exponential-disc decompositions in Simien & de Vaucouleurs (1986). Due to Simien & de Vaucouleurs use of the $R^{1/4}$ model to describe bulges which are better matched with an $R^{1/n}$ profile having $n < \sim 3$, and often around 1 (e.g. Andredakis & Saunders 1994; de Jong 1996; Balcells et al. 2003), too much flux has been assigned to the bulges of their disc galaxies. We have derived the mean bulge-to-total ratios from various studies and show the results in Table 2. On average, the bulge luminosities used by AR02 will be ~ 2 times too bright and thus their estimate of the SMBH mass in the bulges of disc galaxies will be high by a factor of ~ 2 . Correcting for this would result in a 12.5 per cent reduction to their total SMBH mass density, giving a value of $5.2 \times 10^5 M_\odot \text{ Mpc}^{-3}$ ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$). Using Allen et al.'s (2006) Sérsic-bulge + exponential disc decompositions of 10,095 galaxies, we plan to apply the $M_{\text{bh}}-L$ relation from Graham (2007) to obtain a new measurement of $\rho_{\text{bh},0}$.

Regarding the conversion of these overly-bright bulge magnitudes to velocity dispersions, the logarithmic slope of the $L-\sigma$ relation is known to be shallower at fainter luminosities (e.g. Tonry 1981, Held et al. 1992), and for magnitudes below $M_B \sim -19.5 \pm 1$ mag the slope is approximately 2 (de Rijcke et al. 2005; Matković & Guzmán 2005), compared to a value of four for the more luminous spheroids (Faber & Jackson 1976; their figure 16). The use of a constant slope of 3 by AR02 would have therefore systematically under-estimated the velocity dispersion as one progresses to fainter magnitudes, and over-estimated the velocity dispersion in the larger spheroids. Without performing a full re-analysis of their data, the overall corrective term is unknown. In pass-

Table 2. Mean \pm standard deviation of the (bulge minus galaxy) magnitude and bulge-to-galaxy flux ratios, B/T , derived from literature data. (A more complete summary, using other literature data, and a variety of optical and near-infrared passbands will be presented in Graham & Worley 2007, in prep.)

	S0/S0a	Sa,Sab,Sb	\geq Sc
$R^{1/4}$ -bulge plus Exponential-disc			
$(m_{\text{bulge}} - m_{\text{tot}})^a$	0.61 ± 0.32	1.37 ± 0.68	3.22 ± 0.99
$(B/T)^a$	0.59 ± 0.16	0.34 ± 0.20	0.07 ± 0.06
$(m_{\text{bulge}} - m_{\text{tot}})^b$	...	1.67 ± 1.06	3.18 ± 1.41
$(B/T)^b$	...	0.32 ± 0.26	0.11 ± 0.11
Exponential-bulge plus Exponential-disc			
$(m_{\text{bulge}} - m_{\text{tot}})^b$	...	2.70 ± 1.18	4.08 ± 1.03
$(B/T)^b$	...	0.12 ± 0.10	0.04 ± 0.03
$R^{1/n}$ -bulge plus Exponential-disc			
$(m_{\text{bulge}} - m_{\text{tot}})^c$	...	2.36 ± 1.06	4.21 ± 1.06
$(B/T)^c$	...	0.17 ± 0.09	0.03 ± 0.03
$(B/T)^d$	0.25 ± 0.09	...	...
$(B/T)^e$	0.24 ± 0.11	...	...

^a B-band data from Simien & de Vaucouleurs 1986.

^b B-band data from de Jong 1996.

^c B-band data from Graham 2003.

^d K-band data from Balcells, Graham & Peletier 2007.

^e K-band data from Laurikainen, Salo & Buta 2005.

ing we note that the non-linear nature of the $L-\sigma$ relation complicates AR02's prediction of the parameter β shown in their equation 10.

2.2 Case study 2

Our second example is the analysis in Shankar et al. (2004, their section 3.1 & 3.2), who used the $M_{\text{bh}}-L$ relation, in addition to the $M_{\text{bh}}-\sigma$ relation, to estimate ρ_{bh} from various luminosity functions. Their equation 1 for predicting SMBH masses from luminosities was also obtained under the (false) assumption that the SMBH masses which define this relation are dependent on the Hubble constant. They modified the $M_{\text{bh}}-L$ relation from McLure & Dunlop (2002; their equation 6) which had originally been (correctly) constructed with no H_0 -adjustment to the black hole masses. The equation in Shankar et al. therefore requires that $\log(70/50)$ be subtracted from the left hand side¹. Correcting this results in a 40 per cent increase to their $(M_{\text{bh}}-L)$ -estimated SMBH masses and thus a 40 per cent increase in their value of ρ_{bh} . Their h -corrected value for $\rho_{\text{bh},\text{total}}$ is $(5.9 \pm 1.5) \times 10^5 M_\odot \text{ Mpc}^{-3}$ ($h = 0.7$), in perfect agreement with AR02's h -corrected value. Similarly, their equation 3 should not contain the factor $80/H_0$, and so their $(M_{\text{bh}}-\sigma)$ -estimated SMBH masses, and thus their $(M_{\text{bh}}-\sigma)$ -derived

¹ Equation 1 from McLure & Dunlop (2004) should read $\log(M_{\text{bh}}/M_\odot) = 1.25 \log(L_K/L_\odot) - 5.53$, when using $M_{K,\odot} = 3.28$ mag and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. While relevant to the ρ_{bh} adjustments made in Table 3, this is perhaps a moot point given that the galaxy distances and thus absolute magnitudes used to construct that equation are known independently of the Hubble constant, just as the SMBH masses are, see section 3.1 of Graham 2007.

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$\rho_{\text{bh},0}$, needs to be increased by 14 per cent when using their adopted value of $h = 0.7$.

Shankar et al.'s equation 4 for the SMBH mass function, which has ϕ_* in units of $\log M_{\text{bh}}$ (rather than M_{bh}) can be written as

$$\frac{dN}{d \log M_{\text{bh}}} = h^3 \phi_* \left(\frac{M_{\text{bh}}}{M_* h^{-2.5}} \right)^{\alpha+1} \exp \left[- \left(\frac{M_{\text{bh}}}{M_* h^{-2.5}} \right)^\beta \right], \quad (4)$$

where the exponent -2.5 comes from their equation 1 which was used to transform magnitudes M_R into SMBH masses using $\log M_{\text{bh}} \propto -0.5(M_R + 5 \log h)$. The expression for the SMBH mass density is thus

$$\begin{aligned} \rho_{\text{bh}} &= \int_{M_{\text{min}}}^{M_{\text{max}}} M_{\text{bh}} \frac{dN}{d \log M_{\text{bh}}} d \log M_{\text{bh}} \\ &= h^3 \phi_* \frac{M_* h^{-2.5}}{\beta (\ln 10)} \left\{ \gamma \left[\frac{\alpha+2}{\beta}, \left(\frac{M_{\text{max}}}{M_* h^{-2.5}} \right)^\beta \right] \right. \\ &\quad \left. - \gamma \left[\frac{\alpha+2}{\beta}, \left(\frac{M_{\text{min}}}{M_* h^{-2.5}} \right)^\beta \right] \right\}. \end{aligned} \quad (5)$$

A similar parameterisation of the SMBH mass function could be made for the data in McLure & Dunlop (2004) and Marconi et al. (2004), except for the latter study the exponent would be -2.26 rather than -2.5 (see their equation 10). This full dependency on the Hubble constant was not included in Tundo et al.'s (2007) reanalysis of these works. Their $M_{\text{bh}} \propto L^{1.30}$ relation is also considerably steeper than the new expression $M_{\text{bh}} \propto L^{0.93}$ reported by Graham (2007) and it predicts notably larger SMBH masses for galaxies more luminous than $M_R \sim -21$ mag.

In Table 3 we provide updated values of ρ_{bh} and, importantly, show their dependence on the Hubble constant. While some estimates of $\rho_{\text{bh},0}$ appear not to have changed from Table 1, one should note that the quoted dependence on h may have changed, which is of course of importance if $H_0 \neq 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2.2.1 Related issues

Many studies have assumed the universal existence of $R^{1/4}$ light-profiles when obtaining their total galaxy magnitudes, and have thus introduced a systematic bias into their luminosity-derived SMBH mass function. For instance, a light-profile shape dependent — and therefore luminosity dependent (e.g. Graham & Guzmán 2003, their figure 10 and references therein) — magnitude correction (Graham et al. 2005) is applicable to the SDSS Petrosian magnitudes which Shankar et al. used. Adding -0.2 mag to the Petrosian magnitudes, in an effort to recover the total galaxy magnitude, is only applicable if every galaxy has an $R^{1/4}$ light-profile. However, a range of profile shapes has long been known to exist (e.g. Davies et al. 1988; Caon et al. 1993) and is such that a smaller/greater correction for missed flux needs to be applied to the Petrosian magnitudes of galaxies less/more luminous than $M_B \sim -21$ mag (Kormendy & Djorgovski 1989). Similarly, a light-profile shape (and outermost sampled radius) dependent magnitude correction (Graham & Driver 2005, their figure 10) is required for recovering total magnitudes from Kron magnitudes. Indeed, half a galaxy's flux may be missed using Kron magnitudes (Andreon 2002; Bernstein, Freedman, & Madore 2002; Benitez et al. 2004).

3 SUMMARY

Table 3 shows our “ h -corrected” $\rho_{\text{bh},0}$ values. It should be noted that the h -dependent corrections we have detailed effect not only the value of $\rho_{\text{bh},0}$ but also the SMBH mass functions from which these values are typically derived. The related issues we have raised in sections 2.1.1 and 2.2.1 that pertain to the luminosity of the host spheroid have not been included in Table 3. The use of h -independent Sérsic indices and velocity dispersions for constructing the SMBH mass function and mass density results in a purely h^3 dependence for ρ_{bh} . This is because the SMBH masses that are involved are derived from relations which themselves do not depend on any assumed Hubble constant.

We (tentatively) identify previously missed agreements on the value of $\rho_{\text{bh},0}$. For example, AR02's corrected value² of $(5.9 \pm 2.0) \times 10^5 M_\odot \text{ Mpc}^{-3}$ (for $h = 0.7$) is now in good agreement with Merritt & Ferrarese's (2001) ($M_{\text{bh}}-\sigma$)-derived measurement of $4.6 \times 10^5 h_{70}^3 M_\odot \text{ Mpc}^{-3}$. In fact, a (near) consensus on the local SMBH mass density now exists. The $M_{\text{bh}}-L$ based studies are seen to agree with each other and with recent studies which have used a mean SMBH-to-spheroid mass ratio convolved with the local spheroid mass density. The $M_{\text{bh}}-n$ based study (Graham et al. 2007) is also seen to agree with both of these types of analysis, with the optimal (total) SMBH mass densities ranging from $4.6-5.9 \times 10^5 M_\odot \text{ Mpc}^{-3}(h = 0.7)$ for all three types of analysis. Furthermore, some of the h -corrected $M_{\text{bh}}-\sigma$ based studies (Aller & Richstone 2002; Marconi et al. 2004; Shankar et al. 2004) also provide consistent results with this range. The two exceptions are the noticeably lower values of $(2.9 \pm 0.4) \times 10^5 h_{70}^3 M_\odot \text{ Mpc}^{-3}$ (Yu & Tremaine 2002) and $(2.0 \pm 0.4) \times 10^5 h_{70}^3 M_\odot \text{ Mpc}^{-3}$ (Wyithe 2006)³.

Excluding galaxies without ‘secure’ SMBH mass determinations, Marconi et al. (2004) derived and used an $M_{\text{bh}}-\sigma$ relation with a 0.17 dex higher zero-point (and 0.09 steeper slope) than used by Yu & Tremaine (2002). This accounts for their different ($M_{\text{bh}}-\sigma$)-derived values of $\rho_{\text{bh},0}$. It is also worth noting that if the local sample of ~ 30 galaxies with direct SMBH mass measurements have low luminosities with respect to the greater population at any given velocity dispersion (Yu & Tremaine 2002; Bernardi et al. 2007; Tundo et al. 2007; Lauer et al. 2007), then the $M_{\text{bh}}-L$ relation will over-predict $\rho_{\text{bh},0}$. However, as noted by Graham (2007, his Appendix), until accurate bulge/disc decompositions are available for the greater population, and corrections for dust attenuation in the bulges of disc galaxies are addressed (Driver et al. 2007), this remains uncertain.

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² Computing AR02's disc galaxy's bulge luminosities with more realistic B/T flux ratios leads to a 12.5 per cent reduction in $\rho_{\text{bh},0}$, giving a value of $(5.2 \pm 1.8) \times 10^5 M_\odot \text{ Mpc}^{-3}$ (for $h = 0.7$).

³ Correcting Wyithe's (2006) estimate of $\rho_{\text{bh},0}$ for the intrinsic scatter in the $M_{\text{bh}}-\sigma$ relation (see equation 12 in Yu & Tremaine 2002) would only increase it by a factor of 1.1–1.2.

Table 3. Modification of Table 1. Here, the local SMBH mass density estimates have been fully corrected for their dependence on h , and transformed to $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. While some estimates of $\rho_{\text{bh},0}$ appear not to have changed from Table 1, one should note that the quoted dependence on h may have changed. The term $f(h)$ is used to denote that a more complicated dependence on h exists and needs to be taken into account if one is to transform these values to a different Hubble constant (see, e.g. equation 2).

Study	Method	$\rho_{\text{bh},0} (\text{E/S0})$ $10^5 M_\odot \text{ Mpc}^{-3}$	$\rho_{\text{bh},0} (\text{Sp})$ $10^5 M_\odot \text{ Mpc}^{-3}$	$\rho_{\text{bh},0} (\text{total})$ $10^5 M_\odot \text{ Mpc}^{-3}$
Graham et al. (2007)	$M_{\text{bh}} - n$	$(3.46 \pm 1.16)h_{70}^3$	$(0.95 \pm 0.49)h_{70}^3$	$(4.41 \pm 1.67)h_{70}^3$
Wyithe (2006)	$M_{\text{bh}} - \sigma$	...	...	$(1.98 \pm 0.38)h_{70}^3$
Fukugita & Peebles (2004)	ρ_{spheroid}	$(3.4^{+3.4}_{-1.7})h_{70}$	$(1.7^{+1.7}_{-0.8})h_{70}$	$(5.1^{+3.8}_{-1.9})h_{70}$
Marconi et al. (2004)	$M_{\text{bh}} - (L, \sigma)$	$3.3h_{70}^{0.74}f(h)$	$1.3h_{70}^{0.74}f(h)$	$(4.6^{+1.9}_{-1.4})h_{70}^{0.74}f(h)$
Shankar et al. (2004)	$M_{\text{bh}} - L$	$(4.3^{+1.3}_{-1.1})h_{70}^{0.5}f(h)$	$(1.5^{+0.7}_{-0.7})h_{70}^{0.5}f(h)$	$(5.9^{+1.5}_{-1.5})h_{70}^{0.5}f(h)$
Shankar et al. (2004)	$M_{\text{bh}} - \sigma$	$(3.4^{+1.1}_{-0.7})h_{70}^3$	$(1.4^{+0.5}_{-0.3})h_{70}^3$	$(4.8^{+1.2}_{-0.8})h_{70}^3$
McLure & Dunlop (2004)	$M_{\text{bh}} - L$	$(4.8 \pm 0.7)h_{70}^{0.5}f(h)$	...	...
Wyithe & Loeb (2003)	$M_{\text{bh}} - \sigma$	...	...	$(2.1^{+3.4}_{-1.3})h_{70}^3$
Aller & Richstone (2002)	$M_{\text{bh}} - \sigma$	$(4.5 \pm 1.5)h_{70}^{0.39}f(h)$	$(1.4 \pm 1.3)h_{70}^{0.39}f(h)$	$(5.9 \pm 2.0)h_{70}^{0.39}f(h)$
Yu & Tremaine (2002)	$M_{\text{bh}} - \sigma$	$(2.0 \pm 0.2)h_{70}^3$	$(0.9 \pm 0.2)h_{70}^3$	$(2.9 \pm 0.4)h_{70}^3$
Merritt & Ferrarese (2001)	ρ_{spheroid}}$	...	...	4.6h_{70}$
Salucci et al. (1999)	ρ_{spheroid}	$6.2h_{70}^2$	$2.0h_{70}^2$	$8.2h_{70}^2$

Appendix of a different paper. We also thank A.Marconi, D.Merritt, F.Shankar and Q.Yu for their comments.

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